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ROENTGEN STEREOPHOTOGRAMMETRIC ANALYSIS OF GROWTH PATTERN AFTER PRONATION ANKLE INJURIES IN CHILDREN

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ABSTRACT

In a prospective study of ankle fractures in children, the posttraumatic growth pattern was registered with a roentgen stereophotogrammetric technique. This method allows determination of growth rates within three months after fracture, and the prognosis for future growth can be determined within 6-8 months after fracture.

The ankle fractures were classified anatomically according to Salter-Harris and traumatologically according to Gerner-Smidt.

Nine cases were classified as due to pronation: two pronation-abduction injuries and seven pronation-eversion injuries.

The pronation-abduction injuries had Salter-Harris type I injury in distal tibia and fibula, respectively, and showed initial growth stimulation and symmetric growth.

The pronation-eversion injuries had a Salter-Harris type II injury in distal tibia and showed three types of growth pattern: initial growth stimulation (3 cases), growth arrest (2 cases), and progressive growth retardation (1 case), besides one case with no significant growth registered bilaterally. Asymmetric growth within the growth region was found in four cases; in three mainly as a varus position, in one mainly as antecurvation of the ankle joint.

In conclusion, the pronation-abduction injuries showed growth stimulation or symmetric growth, the younger children with pronation-eversion injuries showed growth stimulation, whereas the older showed progressive growth retardation or growth arrest.



INTRODUCTION

The most comprehensive traumatological classification of ankle fractures in children has been presented by Gerner-Smidt (1963). According to this study, pronation injuries constitute mainly two types of trauma: pronation-abduction and pronation-eversion. The value of a traumatological classification concerning ankle fractures in children was previously presented (Kärrholm et al. 1982 a,c).

Different anatomical classifications of physeal injuries in children have been presented for more than a century (Foucher 1863, Poland 1898, Bergenfeldt 1934, Aitken 1936, Salter and Harris 1963), some in order to predict the future growth. The Salter-Harris classification was the most commonly used and found useful (Oh et al. 1974, Salter 1974, 1979, Czitrom et al. 1981). However, during recent years, several authors have reported deformities of varying degree after type I and type II injuries with a presumed favourable prognosis (Stephens and Louis 1974, Lombardo and Harvey 1977, Spiegel et al. 1978, Burkhart and Peterson 1979, Bylander et al. 1981 a, Kärrholm et al. 1982 a). Moreover, the Salter-Harris classification does not comprehend all physeal fracture varieties (Rang 1974), Bylander et al. 1981 a, Kärrholm et al. 1982 a,c) and was recently extended by Ogden (1981).

Concerning ankle injuries, a combination of a traumatological and an anatomical classification has proved of value in diagnosis, treatment, and predicting prognosis after supination-eversion (supination-external rotation), and supination-adduction injuries (Kärrholm et al. 1982 a,b).

This study evaluated the posttraumatic growth pattern after pronation injuries with a roentgen stereophotogrammetric method (Selvik 1974, 1978, Aronson 1976, Rune et al. 1977, Bylander et al. 1981 a,b, Kärrholm et al. 1982 a,b).

MATERIAL AND METHOD

In nine cases, seven boys and two girls aged 8-16 years, with fractures of the ankle, the growth pattern was studied with a roentgen stereophotogrammetric method.

The ankle fractures were classified anatomically according to Salter and Harris (1963) and traumatologically according to Gerner-Smidt (1963) as pronation-abduction or pronation-eversion injuries.

The pronation-abduction injuries are classified into two subgroups: the first type shows a fracture of a medial malleolus (stage Ia) or a ligamentous injury, and a fracture of the lateral malleolus of Salter-Harris type I or II (stage IIa); the second type shows a Salter-Harris type I injury through the distal tibia (stage Ib) and a metaphyseal fracture of the distal fibula (stage IIb).

The pronation-eversion injury shows a Salter-Harris type II injury through the distal tibia with an antero-lateral metaphyseal fragment (stage I-II), metaphyseal fibular fracture (stage III, and a minimal postero-lateral metaphyseal fragment (stage IV) of the distal tibia. The third and fourth stage can usually not be separated and are here considered as an entity.

In this study, one boy 8 years old had a pronation-abduction stage II a injury, and one girl aged 12 years had a stage Ib injury. Six boys aged 10-16 years showed a pronation-eversion stage III-IV injury, as did one girl 13 years old.

Roentgen stereophotogrammetry

For roentgen stereophotogrammetry spherical tantalum balls diameter 0.5 mm are inserted through the surgical wound during general anaesthesia or more commonly percutaneously during local anaesthesia after fracture healing. The insertion is performed with the aid of fluoroscopy. Four tantalum balls are inserted at each side of the growth plate in the distal tibia on the

injured side, whereas usually one tantalum ball is inserted on each side of the growth plate in the distal fibula on both sides and also in the distal tibia on the intact side. In case 1, three tantalum balls were inserted also in the distal fibula on the fracture side. The first examination takes place 2-3 weeks after implantation of markers. The next is performed one month later and then examinations are performed with intervals of 3-6 months during the first years and later with intervals of 6-12 months if there is indication for further follow-up.

At examination, the foot is placed in a Plexiglas calibration cage with markers inserted into the walls. Two X-ray tubes are in use for simultaneous exposure. The body is shielded with a lead apron. The radiation dose of one examination is about one-tenth to one-half of a conventional radiographic examination of the ankle, depending on the technique employed (Kärrholm et al. 1982 b).

The films are evaluated in a precision instrument for aerial photogrammetry (Wild Autograph A8). The co-ordinates for the centre of the bone markers are recorded and related to the laboratory co-ordinate system defined by the calibration cage.

Growth analysis

By computer, the distances between the bone markers at each roentgen examination are calculated and the change in distance between an epiphyseal and a metaphyseal bone marker is calculated as the longitudinal growth. When at least three bone markers at each side of the growth plate are used, the longitudinal growth is calculated as translation of the epiphysis in relation to the metaphysis along the longitudinal axis defined by the calibration cage. Method error of growth evaluation (longitudinal growth) is about 30-50 μm for each roentgen examination corresponding to 0.5-2 μm for the daily growth depending on the length of the time interval between two registrations.

Kinema analysis

When three or more tantalum balls are inserted into the bone on each side of the growth plate, the metaphyseal and epiphyseal markers can be modelled as two rigid bodies in a computer program, enabling calculation of translation and rotation of the epiphysis in relation to the metaphysis between two examinations (Selvik 1974). The error of KINEMA calculation is about 50 μm and $0.1-0.2^\circ$ for translation and rotations, respectively.

RESULTS

Table 1 lists type of trauma, sex, age, skeletal maturity, Salter-Harris classification, displacement, treatment, and posttraumatic growth pattern including accumulated difference in length.

Five types of growth pattern after fracture to the distal tibia or fibula have previously been observed (Kärrholm et al. 1982 a,b): Symmetrical growth ($\rightarrow$), initial growth stimulation of varying length ($\curvearrowright$), initial and temporary growth retardation ($\curvearrowleft$), initial and progressive growth retardation ($\searrow$), and initial and permanent growth arrest ($\downarrow$).

Pronation-abduction

One patient showed symmetrical growth in distal fibula after a stage II injury (case 1). The stage Ib injury (case 2) showed an initial growth stimulation lasting almost eight months after fracture. These injuries were undisplaced and of Salter-Harris type I-II in distal fibula and tibia, respectively.

Pronation-eversion

Three patients 10-12 years of age (case 3-5) showed initial growth stimulation of varying length all in association with asymmetrical growth (Table 2); in case 4 and 5 mainly as a varus position of the distal

Case	Sex	Traumatologic classification	Age at injury	Skeletal maturity*	Salter-Harris Fib.	Displacement	Treatment in addition to plaster	Observation time in months	Tibia		Fibula	
									Growth pattern	Accumulated difference, mm	Growth pattern	Accumulated difference, mm
1	M	PA IIa	8	8.5	-	I or II	< 2	-	↗	1.0	↗	-0.9
2	F	PA Ib	12	13	I	-	< 2	-	↗	0.6	↗	0.6
3	M	PE III-IV	10	10	II	-	> 5	closed red	↗	1.7 [#]	↗	0.1
4	M	"	11	11.5	II	-	> 5	open red. pinning, wire	↗	0.8 [#]	↗	0.3
5	M	"	12	12.5	II	-	2-5	closed red	↗	-2.0 [#]	↗	0.4
6	M	"	13	13.5	II	-	> 5	"	↗	-2.9 [#]	↗	0.6
7	M	"	14	15	II	-	< 2	-	↘	-0.2	↘	-0.6
8	M	"	16	14.5	II	-	> 5	closed red	↘	-1.3	↘	-0.6
9	F	"	13	14	II	-	2-5	"	-	0	-	0

* Skeletal maturity according to Greulich and Pyle (1959).

[#] Asymmetric growth within growth region.

- No significant growth registered bilaterally

Table 2. Rotation of the distal tibial epiphysis about the cardinal axes in four cases with asymmetric growth in the growth plate.

Case	Time of observation (months)	Rotation of distal tibial epiphysis about the cardinal axes		
		Transverse	Sagittal	Longitudinal
3	4 - 21	5.4° antecurv.	2.0° valgus	1.3° ext. rot.
4	2.5 - 7 5	0.4° antecurv.	2.8° varus	1.6° ext. rot.
5	5 - 24	1.4° antecurv.	4.9° varus	2.3° int. rot.
6	3 - 22	4.7° recurv.	12.6° varus	2.2° int. rot.

tibia, in case 3 mainly as an antecurvation. The other three boys (case 6-8) with significant growth rates showed initial and permanent growth retardation or growth arrest. Progressive growth retardation was associated with asymmetrical growth, in case 6 mainly as a varus position of the distal tibial epiphysis.

CASE REPORTS

Pronation-abduction

Stage Ib.

Case 2. Girl 12 years old suffered an ankle injury while exercising long jump. Clinically a swelling was found of the ankle and tenderness laterally and medially at the distal tibial epiphysis.

Radiograms showed no signs of fracture (Fig. 1 a and b). Treatment in a plaster for 3 weeks was performed as a fracture through the growth plate of the distal tibia was suspected. When the plaster was removed, radiograms showed a periosteal callus laterally along the distal tibial metaphysis (Fig. 1 c and d).

Three periods of registration: $3-4\frac{1}{2}$, $4\frac{1}{2}-7\frac{1}{2}$, and $7\frac{1}{2}-14$ months after fracture.

In the distal tibia on the fractured side, growth rates of 15, 14, and 7 $\mu\text{m}/\text{day}$ were registered during the three periods, whereas corresponding values on the intact side were 12, 10, and 6 $\mu\text{m}/\text{day}$.

In the distal fibula, slightly higher growth rates were registered on the fracture side.

Pronation-eversion

Stage III-IV.

Case 3. Boy 10 years old. Run over by a car. Large displacement and

closed reduction was performed immediately in the emergency room. Radiographs after reduction showed a displacement of the distal tibial epiphysis of about 4 mm and widening of the growth plate medially of about 4 mm. Furthermore, the distal fibula was angulated laterally.

Closed reduction under general anaesthesia was performed and postoperative roentgenograms showed a remaining displacement of the distal tibial epiphysis of about 2 mm.

Three periods of registration: 4-5½, 5½-10½, and 10½-21 months after fracture.

During the first period of registration, the growth rate on the fractured side was about twice that of the intact side (fractured side 25 $\mu\text{m}/\text{day}$, intact side 13 $\mu\text{m}/\text{day}$). During the second period, the difference had diminished; at the third period, the growth rates were almost equal.

In the distal fibula, the growth rate was somewhat lower on the fractured side during the first two periods; at the last period, the growth rate was higher on the fractured side (the fractured side: 16, 15, and 14 $\mu\text{m}/\text{day}$, intact side 18, 21, and 7 $\mu\text{m}/\text{day}$).

KINEMA analysis showed mainly a progressive antecurvature of the ankle that 4-21 months after fracture had reached 5.4°.

Fig. 1 Case 2. Pronation-abduction injury stage I.

a - AP. No visible injury

b - Lateral

c - AP. Thin metaphyseal callus laterally (arrow)

d - Close-up of the lateral distal tibial metaphysis



Fig. 1 a

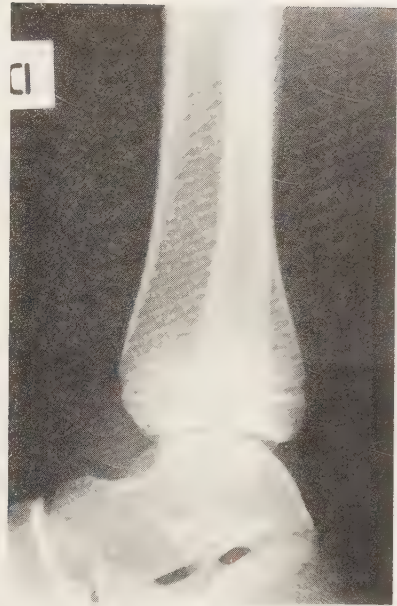


Fig. 1 b



Fig. 1 c



Fig. 1 d

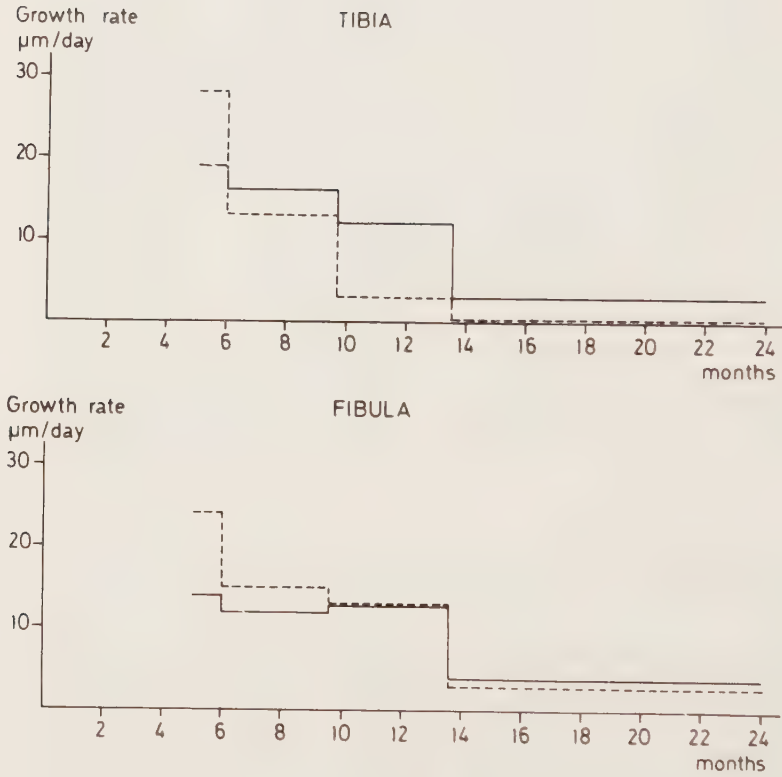


Fig. 2 Case 5. Pronation-eversion stage III-IV.

Diagram shows growth rates in distal tibia (top) and distal fibula (bottom). Full line - intact side. Dashed line - fractured side.

Case 5. Boy aged 12 years, jumped from a height and suffered an ankle fracture.

Radiographically displacement of the distal tibial epiphysis of about 5 mm. Closed reduction during general anaesthesia was performed. Post-operatively radiographs showed a remaining displacement of about 2-3 mm.

Four periods of registration: 5-6, 6-9½, 9½-13½, and 13½-24 months after fracture.

In the injured distal tibia, the growth rate was 28 um/day during first period, decreased down to 13 um (second period) and 3 um (third period), and was 0 fourth period. On the intact side, the growth rate decreased from 19 um/day first period down to 16, 12, and 3 um/day during the following three periods (Fig. 2).

In the distal fibula on the fractured side, the growth rate decreased from 24 down to 3 um/day during the last period. On the intact side the growth rate was about 13 um/day during the first three periods and then decreased down to 4 um/day during the last period (Fig. 2).

KINEMA analysis showed mainly a progressive varus position of the distal tibial epiphysis that after 5-13½ months had reached almost 5°.

Case 6. Boy aged 13 years, while cycling was struck by a car.

At the emergency room, closed reduction was performed. The distal tibial metaphysis was found medially just beneath the skin as the distal tibial epiphysis and the foot were displaced laterally before reduction.

Radiographs showed the distal tibial epiphysis with an antero-lateral metaphyseal fragment displaced one cm laterally and anteriorly. Displacement about 6 mm in the distal fibular fracture (Fig. 3 a and b).



Fig. 3 a



Fig. 3 b



Fig. 3 c



Fig. 3 d



Fig. 3 e



Fig. 3 f

Fig. 3 Case 6. Pronation-eversion stage III-IV.

- a - AP. Distal tibial metaphysis and distal fibula displaced laterally.
- b - Lateral. Displacement anteriorly.

Postreduction radiograms

- c - AP. Remaining displacement about 4 mm.
- d - Lateral.

Radiographs at healing

- e - AP. Valgus position of about 10° .
- f - Lateral. Increased displacement of the distal fragment.

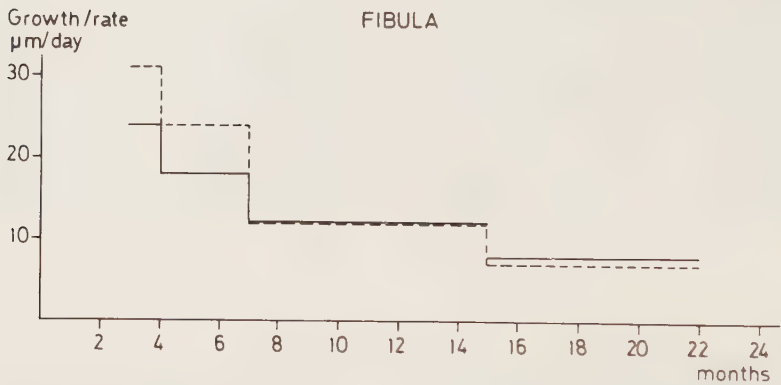
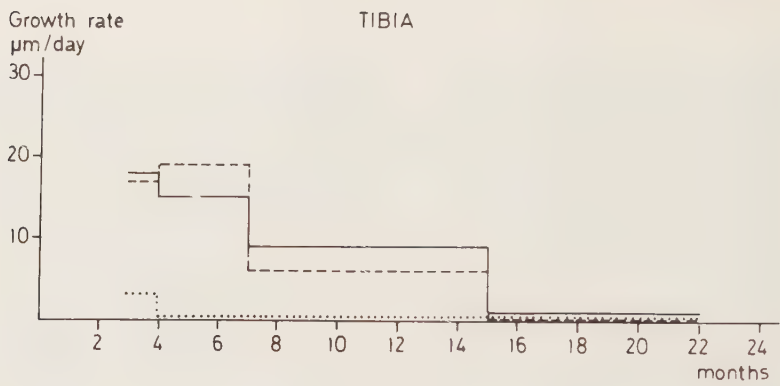


Fig. 3 g

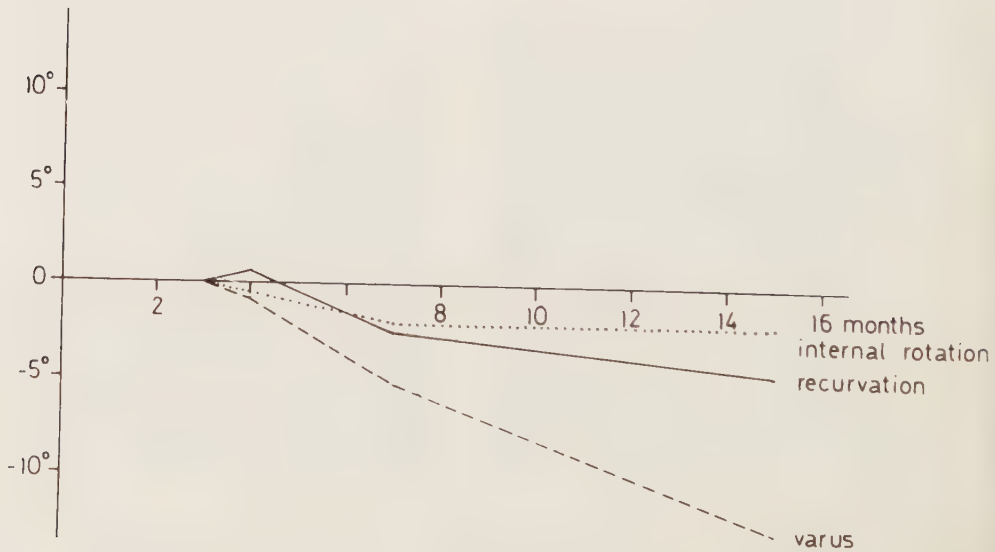


Fig. 3 h



Fig. 3 i



Fig. 3 j

Fig. 3

Growth diagrams

g - Growth rates in distal tibia (top) and distal fibula (bottom).

Full line - intact side. Dashed line - fractured side distal fibula and laterally distal tibia. Dotted line - fractured side medially distal tibia

h - Diagram shows rotational displacement of distal tibial epiphysis in relation to the metaphysis. Full line - rotation about transverse axis. Dashed line - rotation about sagittal axis. Dotted line - rotation about longitudinal axis.

Radiograms 23 months after fracture

i - AP. Varus position of the ankle. Metaphyseal deformity medially due to periosteal reaction.

Growth arrest line laterally, but not medially, in the distal tibial metaphysis.

j - Lateral.

Closed reduction during general anaesthesia was performed and postoperative radiograms revealed a remaining displacement of about 4 mm (Fig. 3 c and d). The fracture healed in a valgus position of about 10° (Fig. 3 e and f).

Four periods of registration: 3-4, 4-7, 7-15, and 15-22 months after fracture.

In the distal tibia on the fractured side the growth rates (mean values) were 8, 6, 2, and 0 $\mu\text{m}/\text{day}$ during the four periods, respectively. Laterally in the distal tibia on the fractured side, the growth rate increased from 17 $\mu\text{m}/\text{day}$ (first period) up to 19 $\mu\text{m}/\text{day}$ (second period). The third period the growth rate decreased down to 6 $\mu\text{m}/\text{day}$; last period, zero. Medially the growth rate was 3 $\mu\text{m}/\text{day}$ (first period). The following periods it was zero. On the intact side, the growth rate decreased from 18 $\mu\text{m}/\text{day}$ during the first period down to 1 $\mu\text{m}/\text{day}$ during the last period (Fig. 3 g).

In the distal fibula on the fractured side, growth rates of 31, 24, 12, and 8 $\mu\text{m}/\text{day}$ were registered during the four periods. Corresponding values for the intact side were 24, 18, 12, and 8 $\mu\text{m}/\text{day}$ (Fig. 3 g).

KINEMA analysis showed progressive varus tilting and recurvation that 3-15 months after fracture had reached 12.6° and 4.7° , respectively (Fig. 3 h).

Radiograms 23 months after fracture showed a slight varus position of the ankle (Fig. 3 i and j).

DISCUSSION

The prognosis of injuries classified as due to abduction or pronation is reported good in the literature (Carothers and Crenshaw 1955, Ehalt 1961, Titze 1967, Duhaime et al, 1972). However, none of these authors separated pronation injuries into rotational (pronation-eversion) or bending

(pronation-abduction) fractures as reported by Gerner-Smidt (1963). Pronation-abduction injuries were separated into two subgroups; subgroup a with fracture of the medial malleolus (stage Ia) and in addition fracture through the growth plate of the distal fibula (stage IIa). First stage without lateral injury show usually no physeal injury (Kärrholm et al. 1982 d); minor problems due to the slight instability (Gerner-Smidt 1963) or delayed healing (Ehalt 1961) are reported and remaining symptoms due to instability have been observed in one case at follow-up four years after trauma (unpublished data).

Growth arrest after injuries to the distal fibula, as in stage IIa, was seen after two cases of atypical fractures; both with an injury to the distal tibia; one of them with symptoms due to lateral dislocation of the talus (unpublished data). Valgus deformity has been observed after an open and displaced pronation-abduction stage IIa injury in a retrospective study (unpublished data). Case one in this study showed, however, symmetrical growth in the distal fibula after a non-displaced stage IIa injury.

The second subgroup (b) of pronation-abduction injuries shows a Salter-Harris type I injury to the distal tibia (stage Ib) and a metaphyseal fibular fracture (stage IIb). The risk of growth disturbance is reportedly low (Aitken 1936, Salter and Harris 1963, Rang 1974, Weber and Süssenbach 1978). Bartl (1957) reported 87 children with this injury; none with growth disturbance. However, only a few of these patients were re-examined. Spiegel et al. (1978) found one out of 21 re-examined cases with shortening due to premature closure of the growth plate. Gerner-Smidt (1963) found two children with valgus position of the ankle. In a retrospective study of ankle fractures in children (unpublished data), valgus position combined with a slight lengthening of the bone was found in three cases out of three re-examined 3-10 years after trauma. In the literature Lovell (1968), Broock and Greer (1970), and Nevelös and Colton (1977) described a rare Salter-Harris type I injury due to rotation with a good prognosis concerning the posttraumatic growth pattern; this was not confirmed by Henke and Kiple (1979). The patient in

this study with a non-displaced injury interpreted as a pronation-abduction fracture showed growth stimulation.

The pronation-eversion injuries showed growth stimulation in the younger children; progressive growth retardation or growth arrest in the adolescents. Asymmetric growth was found mainly as a varus tilting of the ankle as earlier reported by Gerner-Smidt (1963) in three cases. Carothers and Crenshaw (1955) found a spontaneous correction of a residual valgus position in six children with abduction injuries, which was interpreted as the result of correction by growth due to changes of weight-bearing. However, residual valgus deformity due to inadequate reduction was found by Bartl (1957) and Gerner-Smidt (1963). Bartl recommended follow-up of these patients because of risk of progressive growth deformity. Moreover, Spiegel et al. (1978) found no spontaneous correction of displaced Salter-Harris type II injuries. Two patients in this study with a valgus position of the ankle at healing showed correction of the deformity due to asymmetric growth with higher growth rates laterally than medially. Spontaneous correction after displaced ankle fractures is supposed to be possible in the younger child (Weber 1964, Ehlers and Eberlein 1964). In the older child with a pronation-eversion injury and remaining displacement at healing, the deformity can be corrected by a medial growth retardation probably because of damage to the medial part of the growth plate and the perichondral ossification groove (Hansson et al. 1972) and not as the result of weight-bearing. Remodelling of bone tissue in the metaphyseal region has no effect on the position of the bony epiphyses and the joint in relation to the metaphysis and diaphysis.

Farine and Spira (1968) studied the morphology of the growth plate after physeal fractures of different localization. In an injury of PE type, they found that a piece of the growth plate had remained attached to the metaphysis medially on a localized area because of a small elevation of the growth plate. Here the fracture passed not along the zone of calcification but through the uncalcified part of the growth plate. A similar fracture mechanism was later suggested by Ehrlich and Strain (1979) and Ogden (1981). The thin and irregular growth region in the older child

and the damaging mechanism of the trauma with both bending and rotatory components can probably explain the high frequency of growth disturbance in displaced injuries of the ankle in the older child (Kärrholm et al. 1982 a). Moreover, a low growth rate and a thin growth plate, as in the older child, will allow a fibrous scar in the growth plate to ossify resulting in retardation and arrest of growth, whereas in the younger child fusion due to osseous bridging more seldom occurs as a high growth rate in the undamaged part of the growth plate counteracts the fibrous scar.

Asymmetric growth within the growth region is inconsistent with a solid bony fusion in the damaged part of the growth plate, but rather a partly fibrous partly osseous tissue but without fusion between the epiphysis and the metaphysis permitting asymmetric growth as was found in the study by Farine and Spira (1968), and as was suggested by Bylander et al. (1981 a).

Pronation-abduction injuries can appear at lower ages with a large remaining growth (Kärrholm et al. 1982 d). No general conclusions about the posttraumatic growth pattern can be drawn with certainty. However, studies of the growth pattern after supination-adduction injuries (Kärrholm et al. 1982 b) and atypical injuries with fractures through the distal fibular physis, combined with fracture through the distal tibia, have shown that the risk of growth disturbance in the distal fibula is greater when the tibia is injured. Concerning the PA stage Ib injuries, the prognosis is good according to the literature, but the stage IIb injuries have probably a worse prognosis due to a more violent trauma and a larger displacement.

The pronation-eversion injuries appear mainly above 10 years of age; the risk of developing a deformity is high according to the literature and to this study.

In conclusion, follow-up after pronation-abduction (stage IIa and IIb) and pronation-eversion injuries is recommended especially in displaced injuries.

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